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# PATENT SPECIFICATION

(11) 1 382 326

(21) Application No. 14693/72 (22) Filed 29 March 1972
(31) Convention Application No. 131 341 (32) Filed 5 April 1971 in (19)
(33) United States of America (US)
(44) Complete Specification published 29 Jan. 1975
(51) INT CL² H03H 9/00
(52) Index at acceptance H3U 22 33 C

## (54) ADAPTIVE FERROELECTRIC TRANSFORMERS

(71) We, RCA CORPORATION, a corporation organised under the laws of the State of Delaware, United States of America, of 30 Rockefeller Plaza, City and State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to adaptive ferroelectric transformers and particularly to transformers comprising a pair of mechanically coupled piezoelectric capacitors.

An adaptive ferroelectric transformer is a circuit element whose transfer characteristic can be adjusted or set by an adapt or control signal and which will retain that characteristic after the signal has been removed. The adaptive transformer is very similar in structure, operation and performance to an adaptive filter. An important difference between the filter and the transformer is that the transformer's response is flat over a broad frequency range, such as the entire audio frequency spectrum, while the filter's response is limited to narrow frequency regions centered about the mechanical resonant frequencies of the device structure. Consequently, adaptive transformers are potentially useful in a variety of circuits where flat broad band frequency response is required, such as in the direct control of audio amplifier gain in remote control systems in commercial television or speech recognition equipment. In addition, adaptive transformers are useful in control circuits for light dimmers.

The adaptive devices comprise a pair of mechanically coupled ceramic piezoelectric capacitors, at least one of which is ferroelectric. Both the ferroelectric and piezoelectric properties of the capacitor material are utilized in operation of the adaptive transformer, the ferroelectric properties allowing the characteristic to be set by the control signal.

A basic difference between the adaptive resonant filter and the adaptive transformer is that in the transformer, resonant modes of vibration in the input capacitor are suppressed and non-resonant modes of vibration in the input capacitor are preferably limited to those modes having net components of mechanical stress in the same direction. If these components of stress were in opposite directions, the effect would be to cancel each other, either directly in the input capacitor or at the output capacitor, due to the generation of output signals having opposite polarity.

A typical three terminal adaptive ferroelectric transformer comprises two mechanically bonded parallel plate capacitors having a common plate as one electrical contact for the capacitors. The dielectric material of the capacitor is a ceramic composition such as lead zirconate/lead titanate having both piezoelectric and ferroelectric properties. One capacitor functions as the input capacitor and the other capacitor functions as the output capacitor of the transformer. The transfer characteristic, i.e. gain ($V_{out}/V_{in}$) versus frequency, is flat over a number of decades of frequency which is determined by the size of the structure. For example, a 6.5 × 6.5 mm device has a characteristic that is flat over the entire audio frequency spectrum. The gain of the characteristic can be set to any arbitrary value between typical values of −60 dB to −20dB by the application of an appropriate adapt pulse to either its input or output ferroelectric capacitor. Unless the transformer structure is completely potted in a rigid substance, the maximum attainable gain is substantially reduced. A problem, however, exists due to the relatively poor temperature stability characteristics of the potted device, often leading to the necessity of temperature compensating circuits.

According to the invention we provide an adaptive ferroelectric transformer as hereinbefore defined, comprising an input capacitor and an output capacitor, said capacitors being mechanically coupled piezoelectric capacitors, at least one of which possesses ferroelectric properties to enable the gain of the transformer to be controlled by a control signal, one of said capacitors being surface mounted

on a substrate for suppressing resonant mechanical vibrations of said input capacitor while leaving essentially non-resonant vibrations with net components of mechanical stress in one direction thereby creating a single polarity output signal in the output capacitor, and wherein said device is substantially temperature insensitive over its operating tempertature range.

In the accompanying drawings:

FIGURE 1 is a perspective partially cross-sectional view of an unmounted prior art adaptive ferroelectric transformer.

FIGURE 2 is a side cross-sectional view of a potted prior art adaptive ferroelectric transformer.

FIGURE 3 is a perspective partially cross-sectional view of an adaptive ferroelectric transformer which is surface mounted in accordance with the invention.

FIGURE 4 is a side cross-sectional view of a surface mounted device which is also potted.

FIGURE 5 is a graphical representation showing the gain stability characteristics as a function of temperature of unmounted potted adaptive ferroelectric transformers in different encapsulants.

FIGURES 6 and 7 are graphical representations showing gain stability characteristics of similar adaptive ferroelectric transformers as a function of temperature when the transformers are surface mounted on different substrates.

Referring to FIGURE 1 there is shown a prior art unencapsulated and unmounted adaptive ferroelectric device. The device is a sandwich-type structure comprising a first metal contact 12, a first body 14 of ferroelectric material, a common conductive contact 16, a second body 18 of ferroelectric material, which may be of the same composition as the first body 14 of ferroelectric material, and a second metal contact 20. This structure provides two capacitors which are mechanically coupled to each other. The first capacitor comprises the first metal contact 12, the first ferroelectric body 14 and the common conductor 16. The second capacitor comprises the second metal contact 20, the second ferroelectric body 18 and the common conductor 16. Typical dimensions of the adaptive ferroelectric device are 250 mils × 250 mils × 20 mils thick. Typical thickness of the ferroelectric bodies or layers is approximately 7 mils. The common conductor 16 is shown to extend beyond the ferroelectric bodies in order to allow for easy attachment of conductive leads to the common conductor 16. Each of the conductors 12, 16 and 20 are provided with conductor lead pads 22, 24 and 26 and wire leads 28, 30 and 32 respectively.

The ferroelectric materials suitable for this device are not limited to lead zirconate/lead titanate materials. Any ferroelectric material is suitable. For example, materials such as ferroelectric barium titanate and lithium niobate may also be employed, however, the characteristics of the device will change in accordance with the piezoelectric and ferroelectric properties of the materials used. Also, the aforementioned device dimensions are not critical with respect to temperature stability and a wide variety of dimensions may be employed. This unclamped device is not suitable for use as a transformer since flexural vibrational stress modes about the plane of symmetry of the device (i.e. the center of the common contact) cause piezoelectric outputs of opposite polarity to those caused by longitudinal or radial stress modes thereby resulting in a low output.

In FIGURE 2 there is shown the same adaptive ferroelectric device as shown in FIGURE 1 but encapsulated in a suitable substance 34 to enhance non-resonant response and reduce resonant response by helping to suppress resonant modes of mechanical vibrations. This encapsulation tends to preferentially reduce the flexural vibrations thereby resulting in a much higher gain as compared with the unmounted, unspotted structure shown in FIGURE 1 and making this device useful as an adaptive transformer. Typically, gains of unencapsulated devices such as shown in FIGURE 1 are $<0.25$ percent as compared to $>3$ percent gain for encapsulated devices. However, we have found that the encapsulant's ability to properly restrict the flexural vibrations of the transformer structure is a function of temperature and leads to temperature variations of the gain characteristics of the device. In addition, the encapsulant also exerts extreme pressure on the transformer capacitors which can significantly alter the dielectric constant of the ferroelectric material to a lower or clamped value. The pressure results from the high shrinkage or thermal expansion coefficients of the encapsulant relative to that of the ferroelectric material.

We have discovered that high values of maximum gain of an adaptive ferroelectric transformer together with temperature stability can be achieved only if the non-resonant vibrations of the transformer structure are restricted to essentially one type or combination of types of vibrations that yield the same polarity output signals and where the means for restricting said vibrations is not significantly temperature sensitive. We have found that by surface mounting the ferroelectric transformer on a rigid substrate, non-resonant vibrations can be essentially limited to radial vibrations (as opposed to flexural vibrational modes) which yield the same polarity output signal and hence result in high gain, while at the same time significantly reducing temperature instability occurring in potted devices. In addition, the dielectric con-

stant does not change significantly when the device is surface mounted. By a rigid substrate, it is meant that the substrate is essentially free of significant flexural movement. Alternatively, a structure is provided so that if substantial flexure occurs, it is about a plane which lies below the center of the mounted capacitors. Then the polarity of the net piezoelectric output due to the flexural components of stress and piezoelectric output due to the radial components of stress will be additive and gain will be high. Radial vibrations are those vibrations in a plane parallel to the surface of the device.

A typical surface mounted device is shown in FIG. 3. The basic transformer structure, that is the mechanically coupled pair of ceramic capacitors, is the same as that shown in FIGURE 1. Here, however, the second metal contact 20 is bonded to a rigid ceramic substrate 36 by a very thin (about 1 mil) layer 38 of an epoxy cement. A high temperature thermal setting epoxy is preferred in order to maintain a rigid bond between the substrate and the transformer over the entire operating temperature range of the device.

Only a thin layer of this cement is used in order to minimize any pressures exerted on the adaptive ferroelectric transformer structure by shrinkage of the epoxy during curing process. The substrate material must be sufficiently rigid and thick that the resultant structure will be difficult to excite into flexural vibration. The substrate material should also preferably be selected to have an expansion coefficient close to that of the transformer material. This will help to minimize temperature dependent pressures exerted on the transformer structure. Substrate materials such as Pyrex glass (Registered Trade Mark), fused quartz, sintered ceramics and brass are preferred. Typical substrate thicknesses are several times the thickness of the transformer. The thicker the substrate, the lower the magnitude of flexural vibration. Typically, the substrate thickness is at least three times the thickness of the transformer to substantially eliminate flexural vibrations. Another advantage of a thick substrate is to reduce the resonant frequency amplitude and to shift the resonant frequency of flexural vibrations to higher values, thus extending the range of the device where a flat output response is obtained.

While materials such as epoxides are useful as substrates, they are not preferred because of their higher expansion coefficients and lower temperature stability as compared to the inorganic substrates mentioned above. An alternative means for mounting the transformer capacitor onto the substrate is by brazing. For example, a ceramic substrate may be provided with a molybdenum surface onto which nickel or copper may be plated and the capacitor then brazed on.

A comparison of the temperature stability of the gain characteristics, capacitance and maximum gain of unencapsulated, encapsulated and surface mounted transformers is presented in Table I and FIGURES 5 through 7.

FIGURE 5 shows the percent change in gain of unmounted encapsulated transformers as the temperature is changed from room temperature. It can be seen with reference to the Table that samples 2—4 shown in FIGURE 5 employ different encapsulants. The deviation in gain is a function of the particular encapsultant. Deviations of from −15 to +40% are observed for sample 4, while the deviation for sample 2 is about −14 to +6% in the temperature range from 0° C. to 80° C. The improved temperature stability achieved by surface mounting can be seen with reference to the curves for samples 5—10 in FIGURES 6 and 7. Here, over the same temperature range sample 9 has one of the largest deviations ranging from about −5 to +5% while the deviations of sample 10 are from about −4 to 0%. Consequently, surface mounting results in improved temperature stability.

TABLE I

A Comparison of Characteristics of Devices Fabricated with Identical Transformer Structures But Different Mounting Techniques

| Sample | Description [a, b] | Maximum[c] Gain (%) | Mounted Side[d] ΔC (%) | Open Side[d] ΔC (%) | [c, e] Δ(%) |
|---|---|---|---|---|---|
| 1 | Unencapsulated | 0.25 | 0 | 0 | – |
| 2 | Encapsulated in A | 7.7 | -5 | -5 | 15 |
| 3 | Encapsulated in B | 5.5 | -40 | -40 | 42 |
| 4 | Encapsulated in C | 3.7 | -50 | -50 | 51 |
| 5 | Surface mounted on Pyrex (Registered Trade Mark) [f] | 4.6 | +10 | +2 | 8 |
| 6 | Surface mounted on Fused Quartz [f] | 6.1 | +5 | +2 | 10 |
| 7 | Surface mounted on Ceramic [g] | 6.3 | -4 | -5 | 6 |
| 8 | Surface mounted on Brass [f] | 5.5 | -25 | -5 | 4 |
| 9 | Surface mounted on C [f] | 6.8 | -25 | -5 | 9 |
| 10 | Surface mounted on Ceramic + Dh + Bi | 6.0 | -5 | -2 | 5 |

NOTES FOR TABLE I:

A – Casting compound with hardener.

B – Another casting compound with hardener.

C – Another casting compound without hardener.

D – Silicone resin –

a – All samples have identical rectangular transformer structure – 250 mils × 250 mils by 20 mils thick. Capacitor thickness approximately 7 mils.

b – All samples have the same ceramic ferroelectric material.

This ferroelectric material has a piezoelectric coupling coefficient (Kp) that is substantially flat over the temperature range considered.

c – When applicable, the mounted capacitor is taken as the output capacitor. The in put equals a 1 volt rms sine wave at 5 kHz.

d – Capacitance measured after fabrication compared to the capacitance of an unencapsulated or unmounted transformer which is approximately 4800 pF.

e – Sum of the magnitudes of the maximum positive and negative gain deviations in the temperature range 5 to 80°C

f – Rectangular substrate approximately 250 mils × 250 mils by 100 mils thick.

NOTES (Continued)

g – Ring shaped substrate approximately 320 mils O.D., 100 mils I.D. by 65 mils thick.

h – Conformal coating of D.

i – Device totally encapsulated in B after conformal coating of D.

It can be seen from the Table that the temperature stability of the gain of surface mounted devices is superior compared to the encapsulated devices while still maintaining a high value of maximum gain. The gain values of surface mounted devices are shown to be stable within a few percent over the temperature range of 5 to 80° C. The capacitance values of surface mounted devices are generally higher than those of the encapsulated devices, being nearly equal to and in some cases greater than the capacitance of an unencapsulated device. The higher capacitance values correspond to the substrates with the lowest thermal expansion coefficients. As indicated by the Table, a ceramic substrate for mounting the adaptive ferroelectric transformer is preferred in order to achieve the combination of high gain and good temperature stability as well as small deviations in capacitance. The particular gain versus temperature characteristic of the ferroelectric transformer is also dependent upon the ferroelectric material employed. Therefore, different temperature characteristics may be obtained upon selection of different ferroelectric materials in the capacitor.

Sample 10 in the Table refers to an adaptive ferroelectric transformer as shown in FIGURE 4. In some instances, for structural or other reasons, potting of a surface mounted adaptive ferroelectric transformer may be desired. In the case of a surface mounted transformer, the encapsulant does not have to restrict flexural vibrations as in the case of encapsulated transformers which are not surface mounted. Consequently, the transformer structure can be protected from epoxy induced stresses by placing a conformal rubberized coating over the structure prior to its encapsulation. Although the coating may not totally absorb the stresses, the temperature characteristics of the resultant device will still be good. Referring to FIGURE 4, there is shown the surface mounted device described with reference to FIGURE 3. The device now includes, however, a rubberized coating 42 which is a few mils thick and which conforms to and covers the exposed surface of the surface mounted transformer. Encapsulant 44 is then provided over the coating 42 so as to encapsulate the ferroelectric transformer. As can be seen with reference to Sample 10 in Table I and FIGURE 7, the characteristics of this device are only slightly different from that of a comparable but unencapsulated surface mounted device.

WHAT WE CLAIM IS:—

1. An adaptive ferroelectric transformer as hereinbefore defined comprising an input capacitor and an output capacitor, said capacitors being mechanically coupled piezoelectric capacitors, at least one of which possesses ferroelectric properties to enable the gain of the transformer to be controlled by a control signal, one of said capacitors being surface mounted on a substrate for suppressing resonant mechanical vibrations of said input capacitor while leaving essentially non-resonant vibrations with net components of mechanical stress in one direction thereby creating a single polarity output signal in the output capacitor, and wherein said device is substantially temperature insensitive over its operating temperature range.

2. A transformer as claimed in claim 1 wherein the piezoelectric material of said capacitors has a coupling coefficient having an essentially flat temperature response.

3. A transformer as claimed in claim 1 or 2 wherein said substrate is a rigid substrate as herein defined.

4. A transformer as claimed in claim 1, 2 or 3 wherein one of said mechanically coupled capacitors is surface mounted on said substrate by means of a thin layer of an epoxy cement.

5. A transformer as claimed in claim 4 wherein said layer of epoxy cement is substantially of 1 mil thick.

6. A transformer as claimed in any one of claims 1 to 5 wherein said substrate is selected from the group consisting of glass, quartz, ceramic and brass.

7. A transformer as claimed in any one of claims 1 to 5 wherein said substrate is a ceramic body.

8. A transformer as claimed in any one of claims 1 to 7 wherein said substrate thickness is at least three times the total thickness of the mechanically coupled capacitors.

9. A transformer as claimed in claim 1 or 2 wherein the thickness of said substrate is such that flexure of said structure occurs about a plane which lies below the centre of the mounted capacitors whereby the polarity

of the net output signal due to flexure is the same as that due to radial stress components.

10. An adaptive ferroelectric transformer as hereinbefore defined substantially as described with reference to FIGURES 3, 4, 6 and 7 of the accompanying drawings.

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Printed for Her Majesty's Stationery Office by the Courier Press, Leamington Spa, 1975.
Published by the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

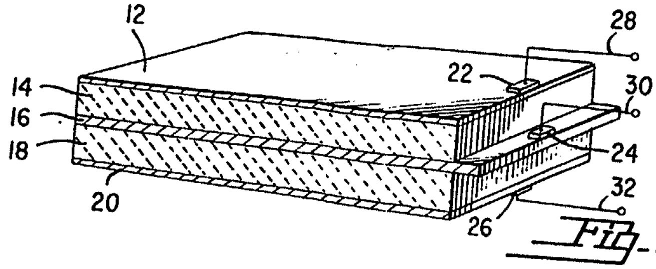
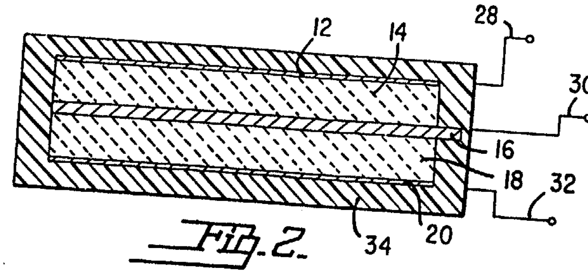



Fig. 1.

PRIOR ART




PRIOR ART

Fig. 2.

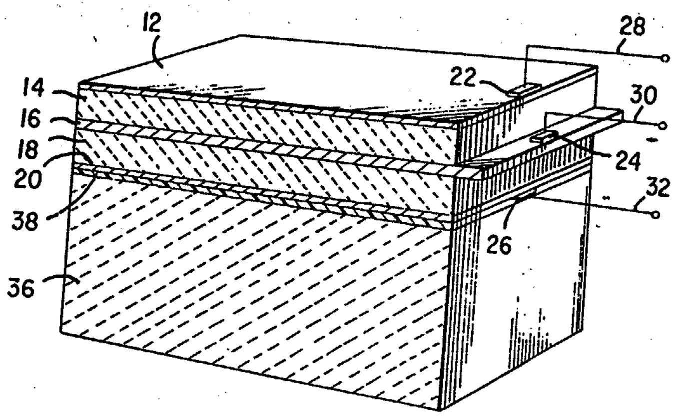
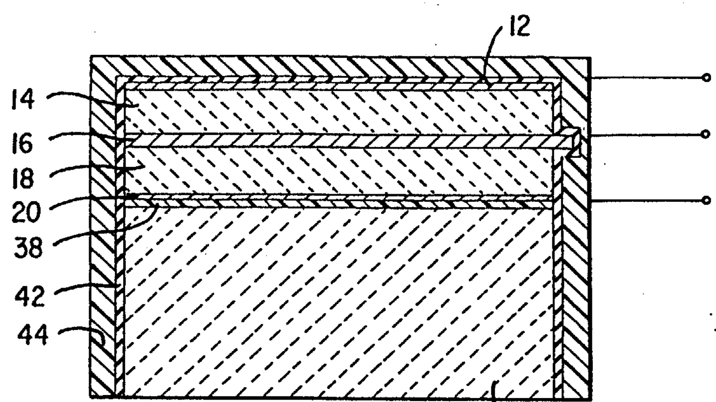



Fig. 3.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44
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Fig. 4.

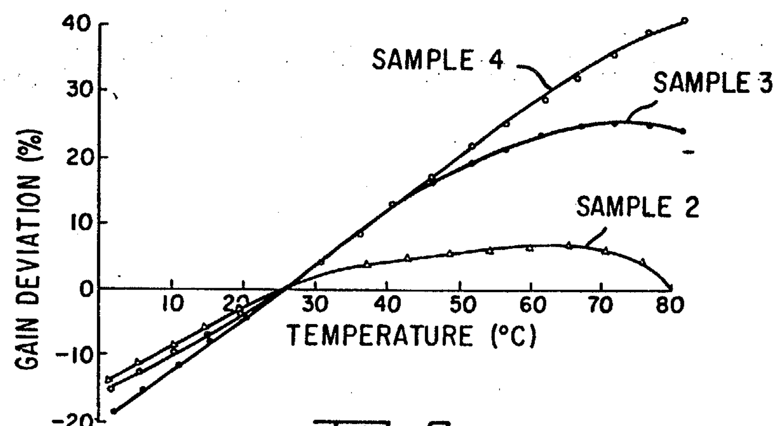
SAMPLE 4
SAMPLE 3
SAMPLE 2
GAIN DEVIATION (%)
TEMPERATURE (°C)
40
30
20
10
0
-10
-20
10
20
30
40
50
60
70
80

Fig. 5.